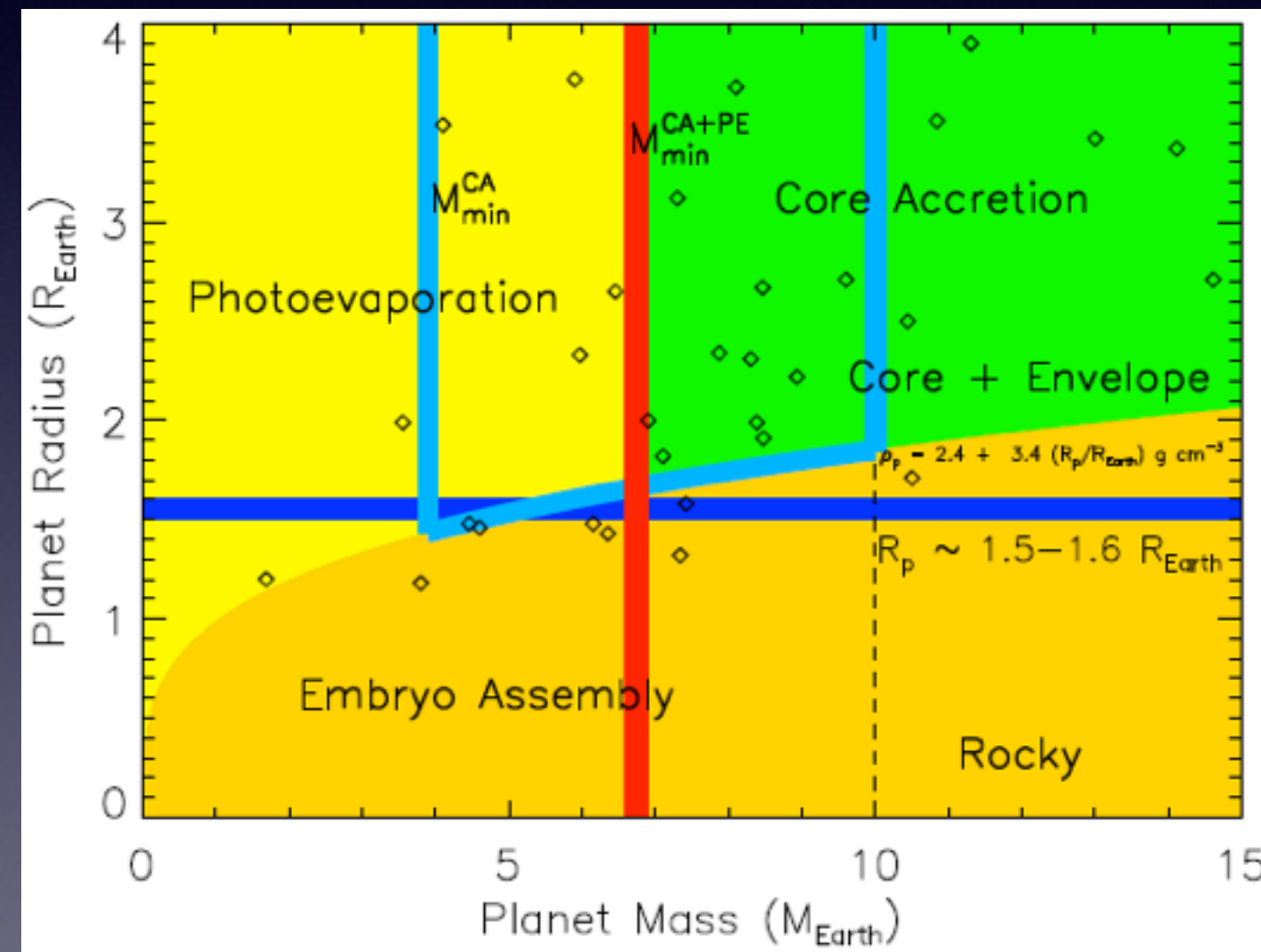


# Super-Earths as Failed Cores in Orbital Migration Traps

Yasuhiro Hasegawa  
(Jet Propulsion Laboratory,  
California Institute of Technology)

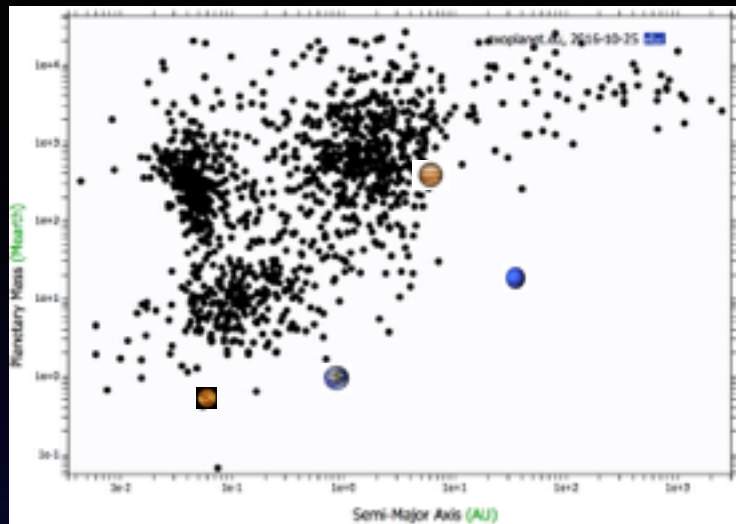


Hasegawa 2016, ApJ, 832, 83



# (Potential) Links to Formation Processes of Planets

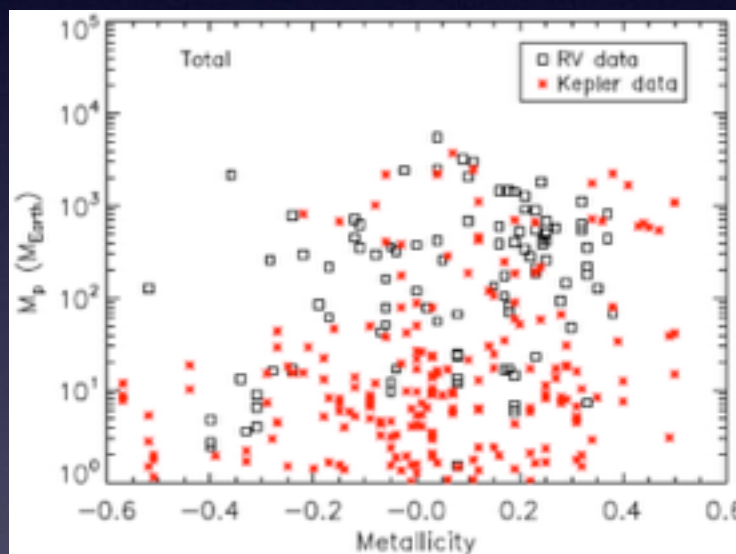
e.g., Winn & Fabrycky 2015



## The Mass-Semimajor Axis Diagram

- : >3300 confirmed (>4600 candidates)
- : rare ( $\sim 1\%$ ) Hot Jupiters, more warm Jupiters & the most dominant super-Earths

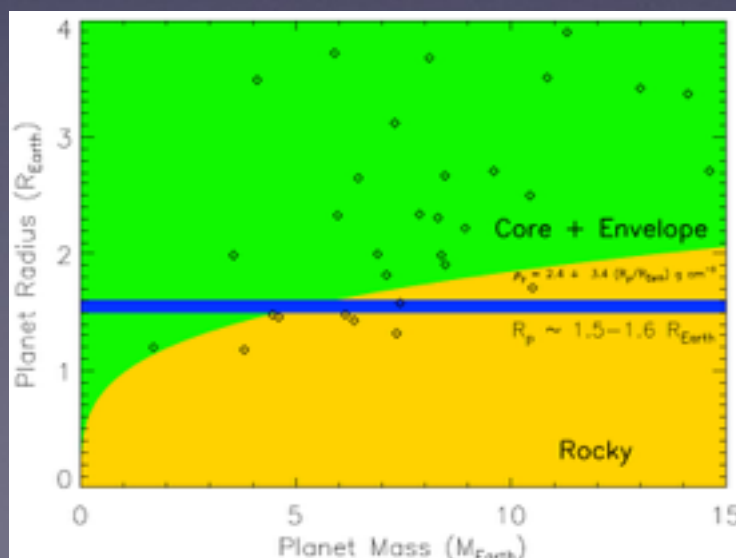
=> The Most Fundamental Figure



## The Planet-Metallicity Relation

- : massive planets are observed higher frequencies around higher metal stars
- : no such correlation for super-Earths

=> Core Accretion Scenario is Preferred



## The Mass-Radius Diagram for Close-in Planets

- : smaller ( $< 1.5-1.6 R_{\text{Earth}}$ ) sized planets tend to be purely rocky
- : larger planets tend to be cores + envelopes

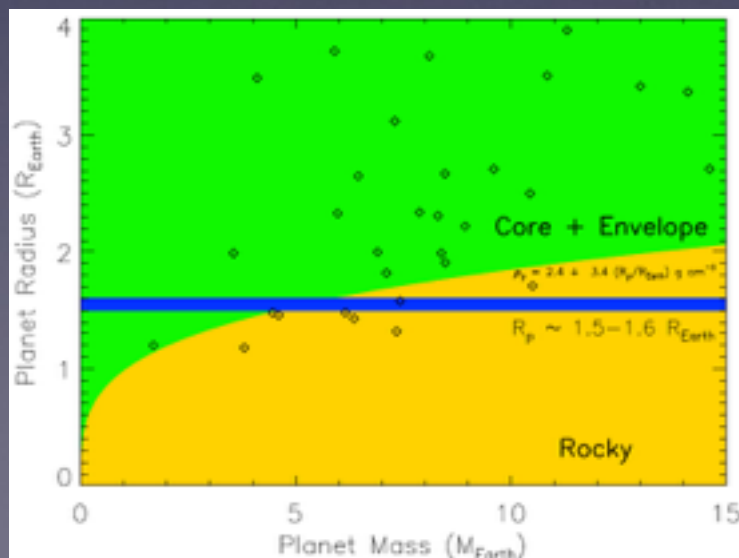
=> ???

# (Potential) Links to Formation Processes of Planets

e.g., Winn & Fabrycky 2015

## The Mass-Semimajor Axis Diagram

The Mass-Radius Diagram is Useful to Identify the Formation, Migration, & Evolution Histories of Close-in Super-Earths



## The Mass-Radius Diagram for Close-in Planets

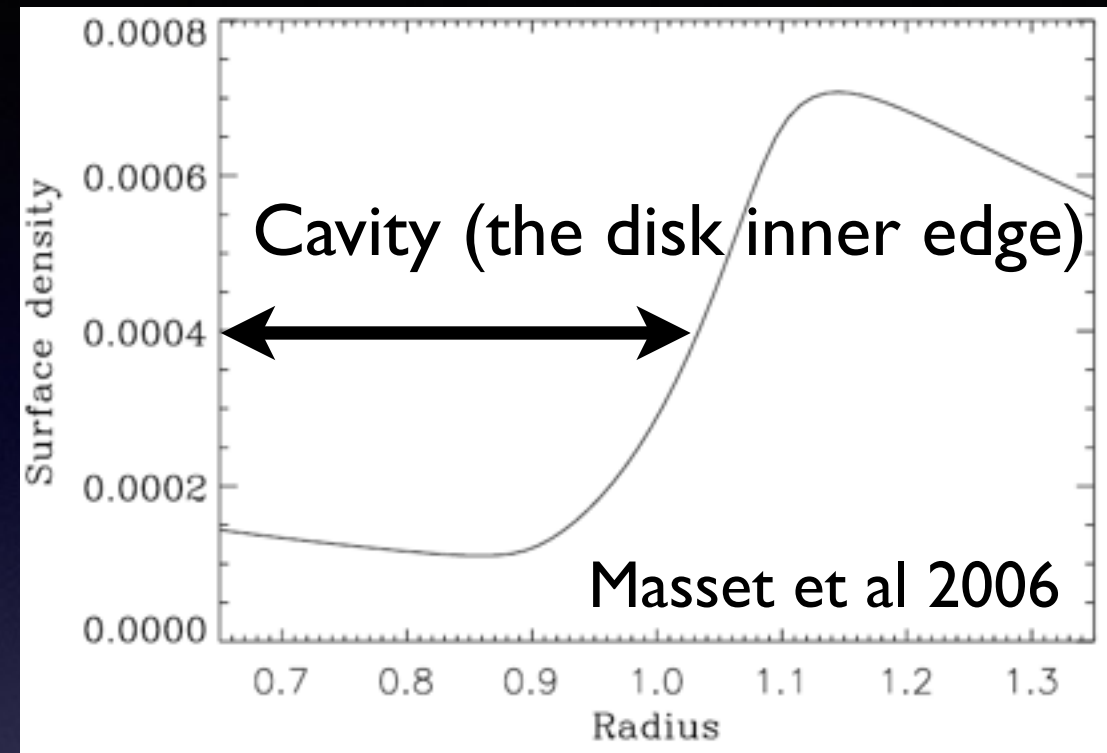
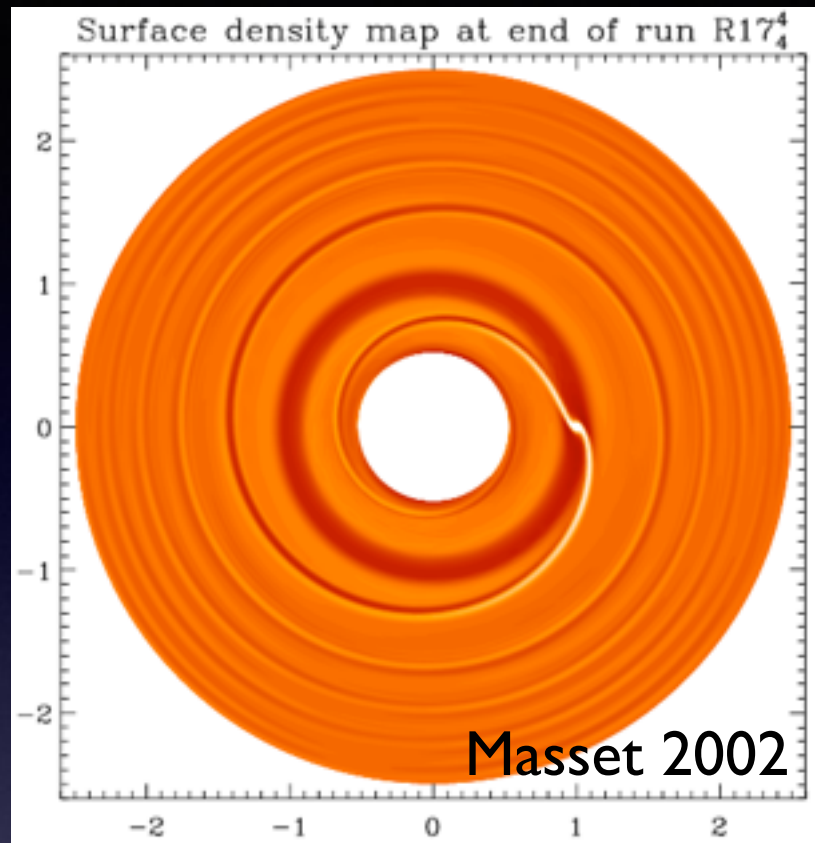
: smaller ( $< 1.5-1.6 R_{\text{Earth}}$ ) sized planets tend to be purely rocky  
: larger planets tend to be cores + envelopes

=> ???



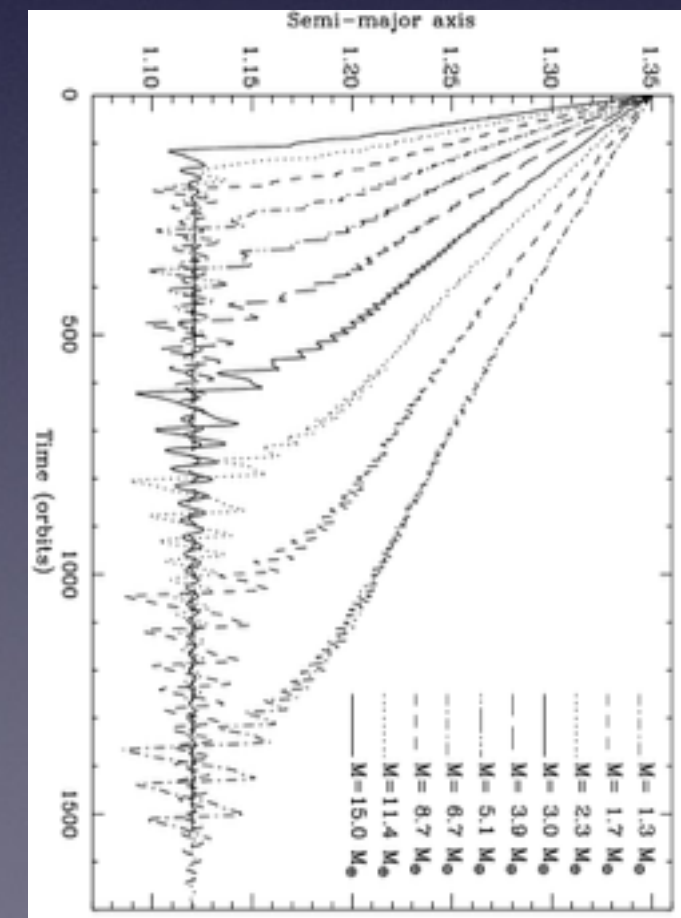
# Key Idea: Type I Migration Traps (Planet Traps)

e.g., Masset et al 2006, Hasegawa & Pudritz 2011b



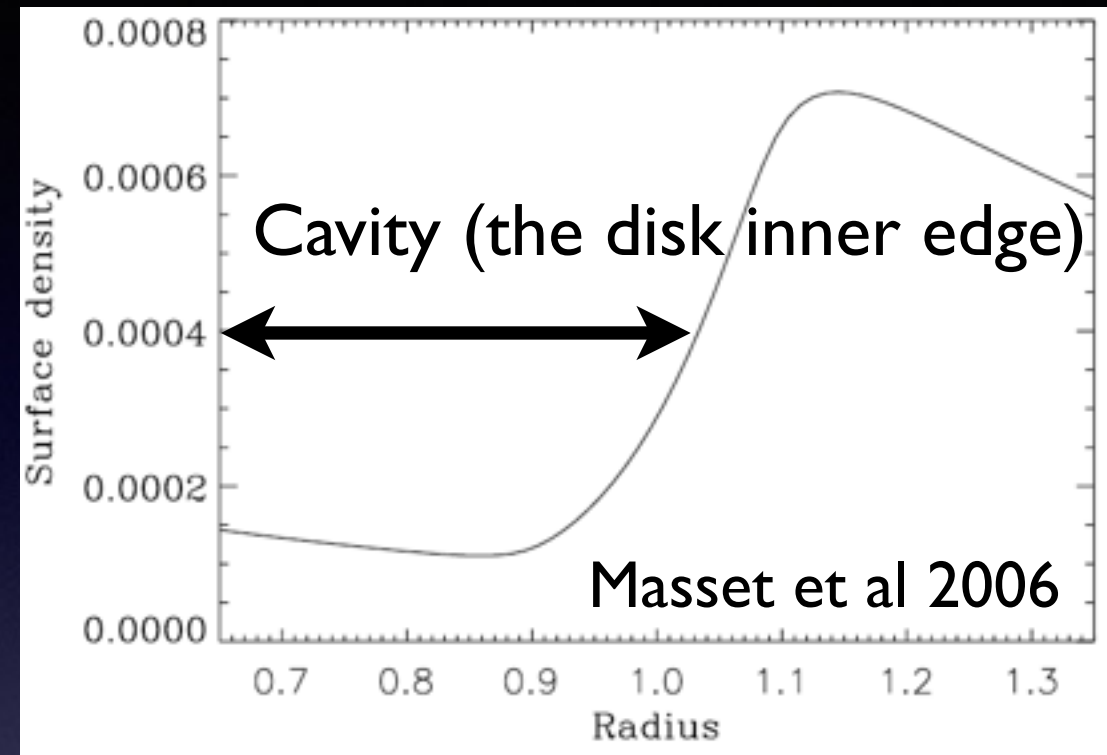
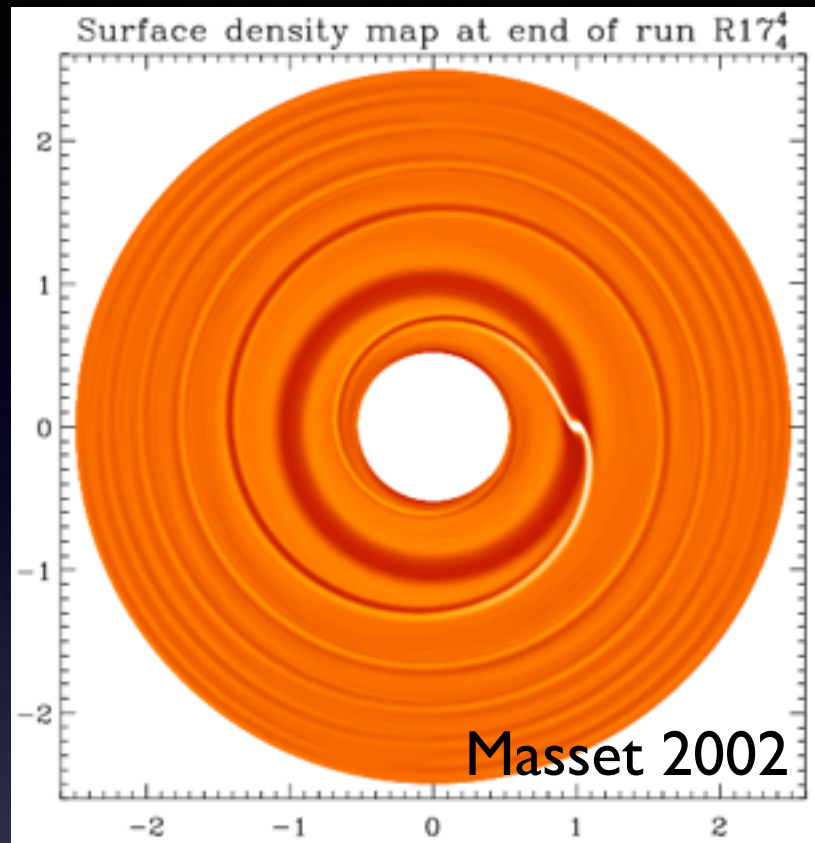
Planetary Migration =  
Angular Momentum Transfer  
between Planets and Gas Disks

The **Net** of Transferred  
Angular Momentum Regulates  
the **Direction** of Migration



# Key Idea: Type I Migration Traps (Planet Traps)

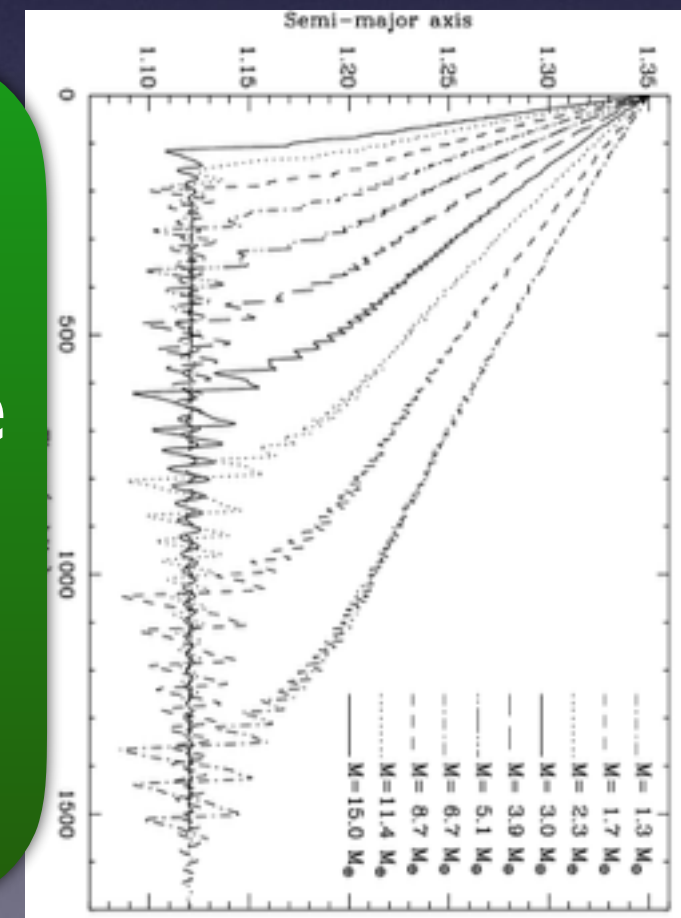
e.g., Masset et al 2006, Hasegawa & Pudritz 2011b



Planetary Migration =  
Angular Momentum Transfer  
between Planets and Gas Disk

The **Net** of Transferred  
Angular Momentum Regulates  
the **Direction** of Migration

Planet Traps =  
Disk Structures  
where the Net Torque  
becomes Zero  
(i.e. Dead Zones,  
Ice Lines, etc..)



# Fundamental Properties of Planet Traps

e.g., Hasegawa & Pudritz 2011b

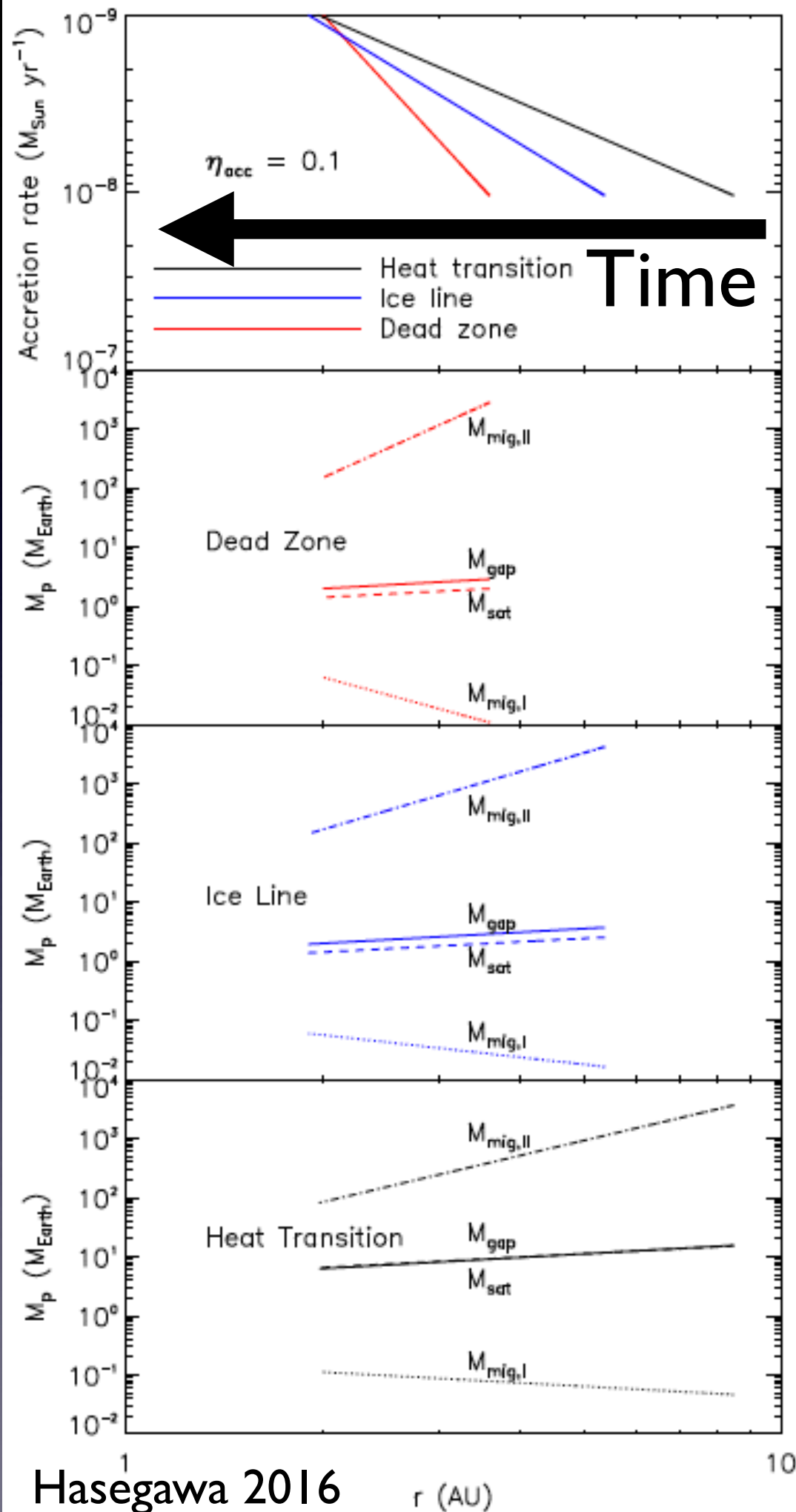
## Multiple Traps in Single Disks

: the outer edge of dead zones, ice lines, heat transitions

## Locations of Traps are Specified by Disk Evolution

## Mass Dependence of Traps

: planet traps are effective until protoplanets obtain the gap-opening mass & undergo type II migration



Planets Form Locally  
at Traps ( $r > 1 \text{ AU}$ )  
Before Type II Migration



# Step 1: Evolutionary Tracks of Trapped Planets

## Disk Evolution

e.g., Hartmann et al 1998

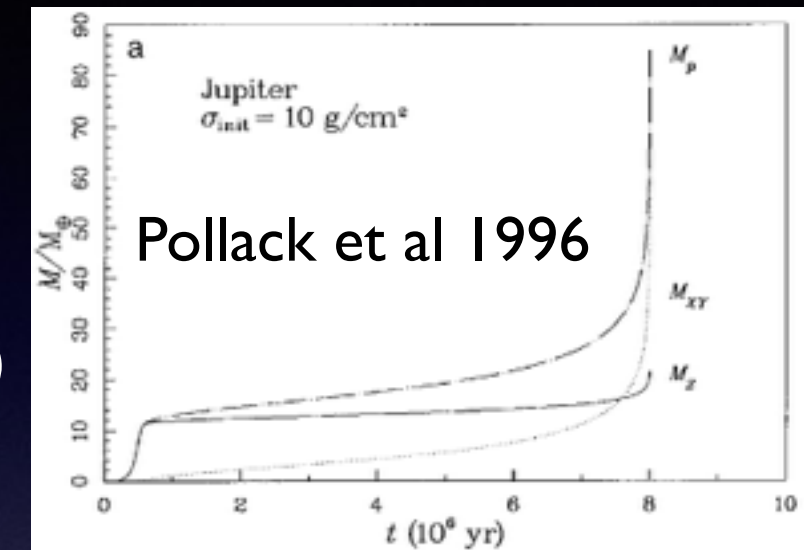
Hasegawa & Pudritz 2012

## Planetary Migration (Orbital Evolution)

Planet Traps for Low Mass Planets

Type II for Massive Planets (w/ a Gap)

## Core Accretion (Mass Growth)



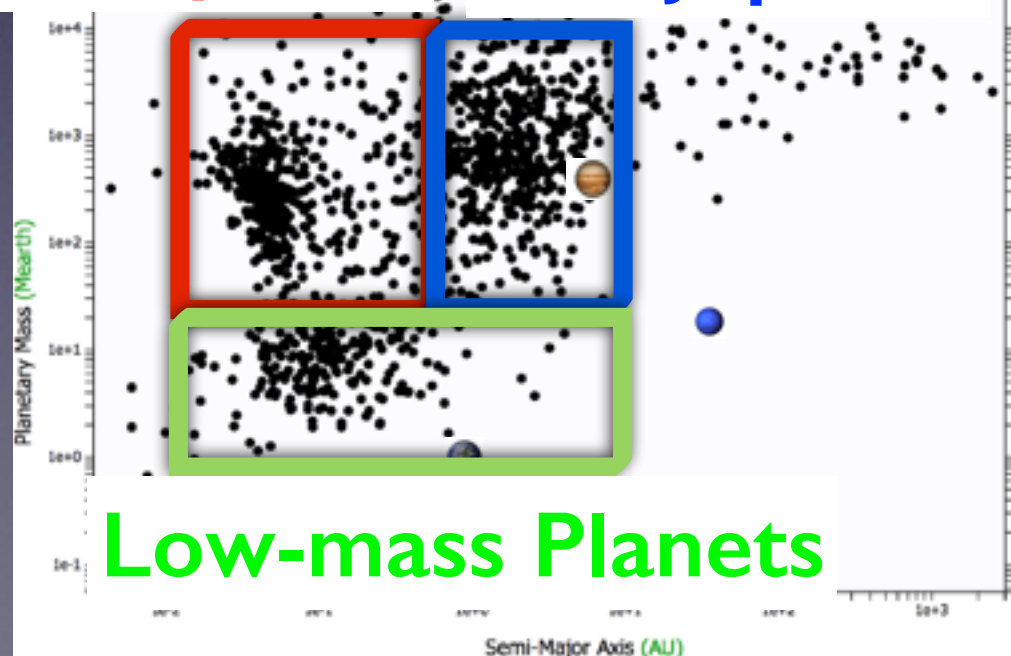
# Step 2: Statistical Analysis for Computed Tracks

Hasegawa & Pudritz 2013

## Partition the Diagram

Hot Jupiters

Exo-Jupiters



Low-mass Planets

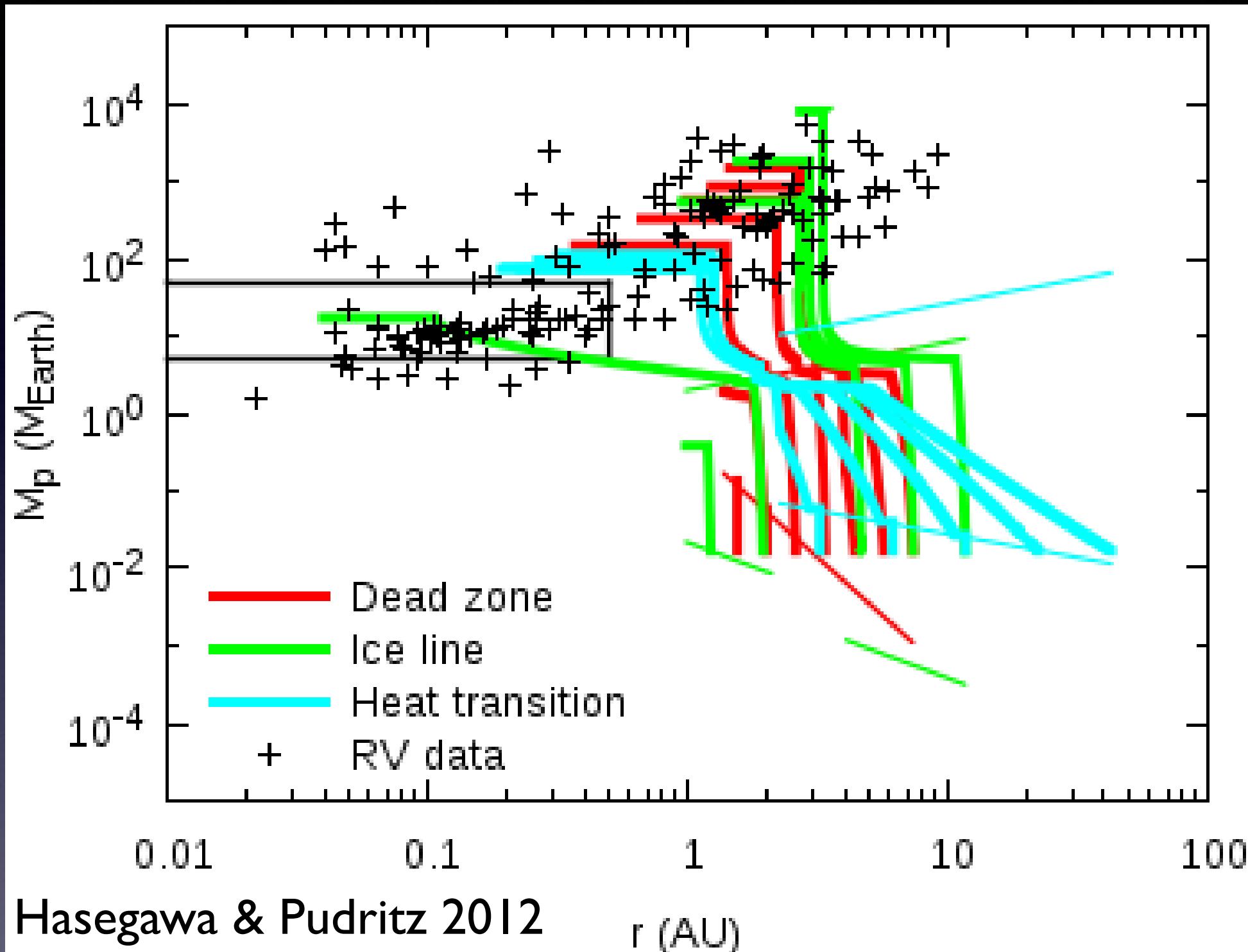
## Calculate Planet Formation Frequencies (PFFs)

$$PFFs \equiv \sum_{\eta_{acc}} \sum_{\eta_{dep}} \frac{N(\eta_{acc}, \eta_{dep})}{N_{int}}$$

$$\times w_{mass}(\eta_{acc}) w_{lifetime}(\eta_{dep})$$

Weight functions related to disk observations

# Result I: Quick Look



Dead Zone Traps:  $r \sim 1 \text{ AU}$

Ice Line Traps:  $0.03 \text{ AU} < r < 3 \text{ AU}$

Heat Transition Traps:  $r \sim 0.3 \text{ AU}$

End-Points of Tracks

Line-up with the RV Data



## Result 2: Quantitative Analysis

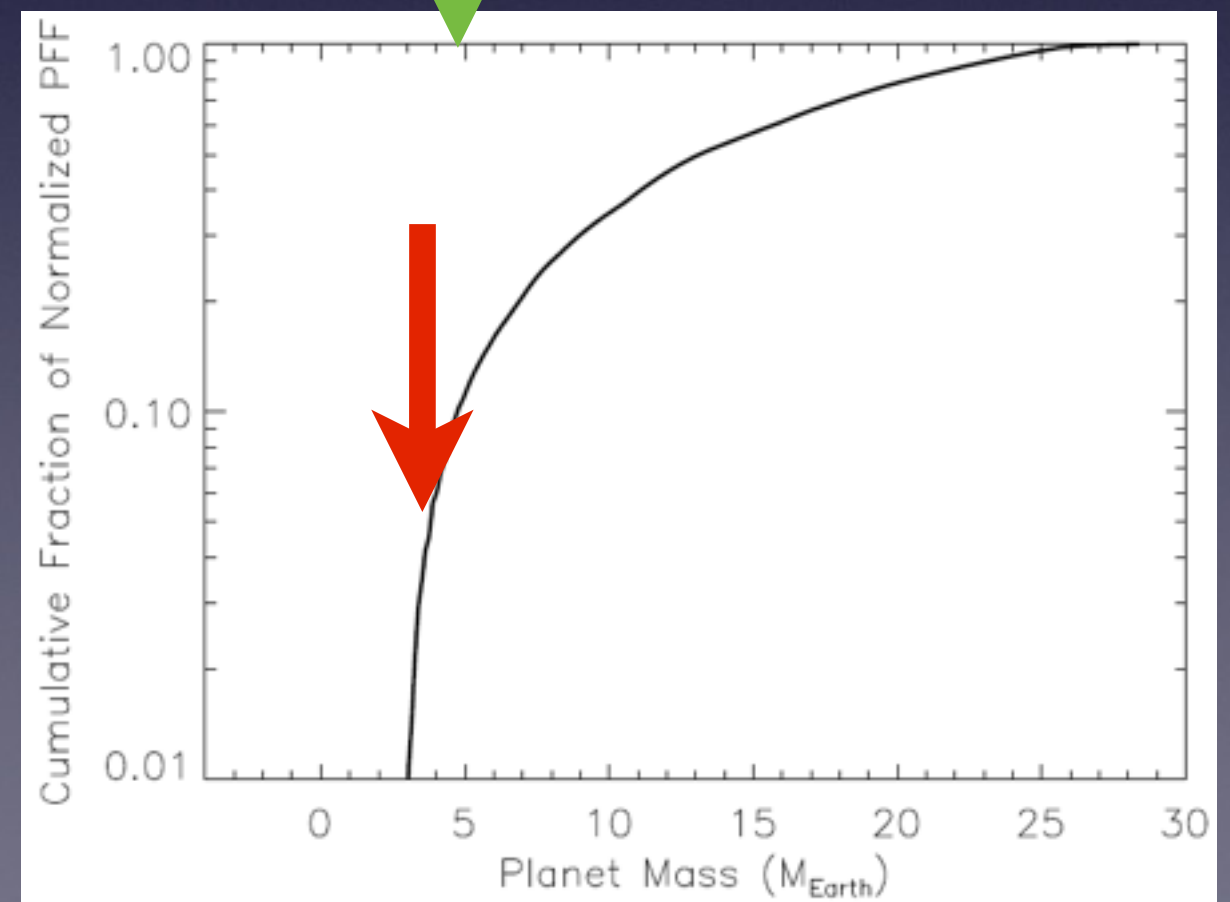
Hasegawa 2016

$1M_{\odot}$	Hot Jupiters	Exo-Jupiters	Super-Earths	Total
PFF	$\sim 7.6 \%$	$\sim 25.3 \%$	$\sim 10.2 \%$	43.1%

A Considerable Fraction of Observed Super-Earths may be Formed as Failed Cores of Gas Giants (Mini-Gas Giants)

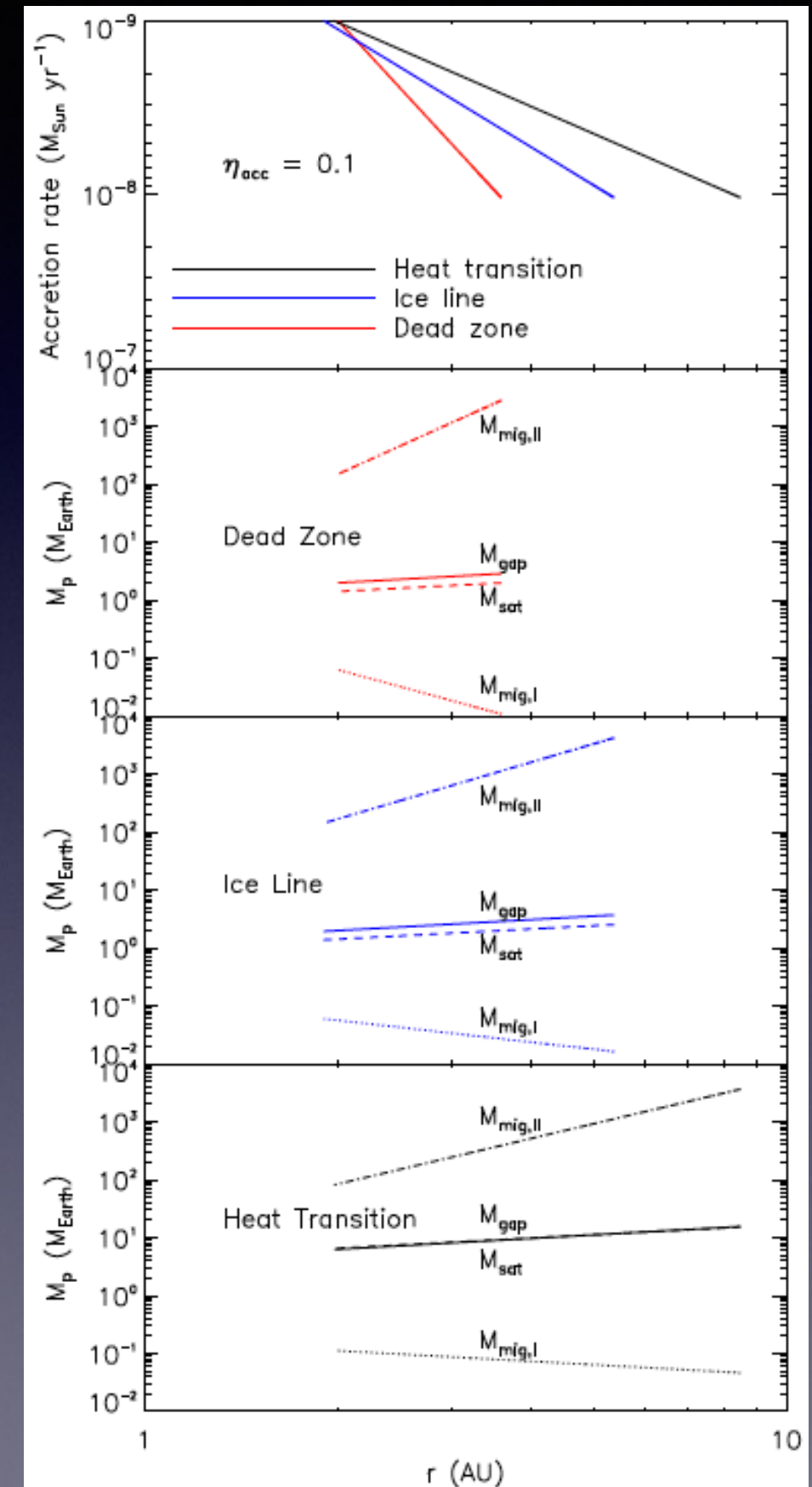
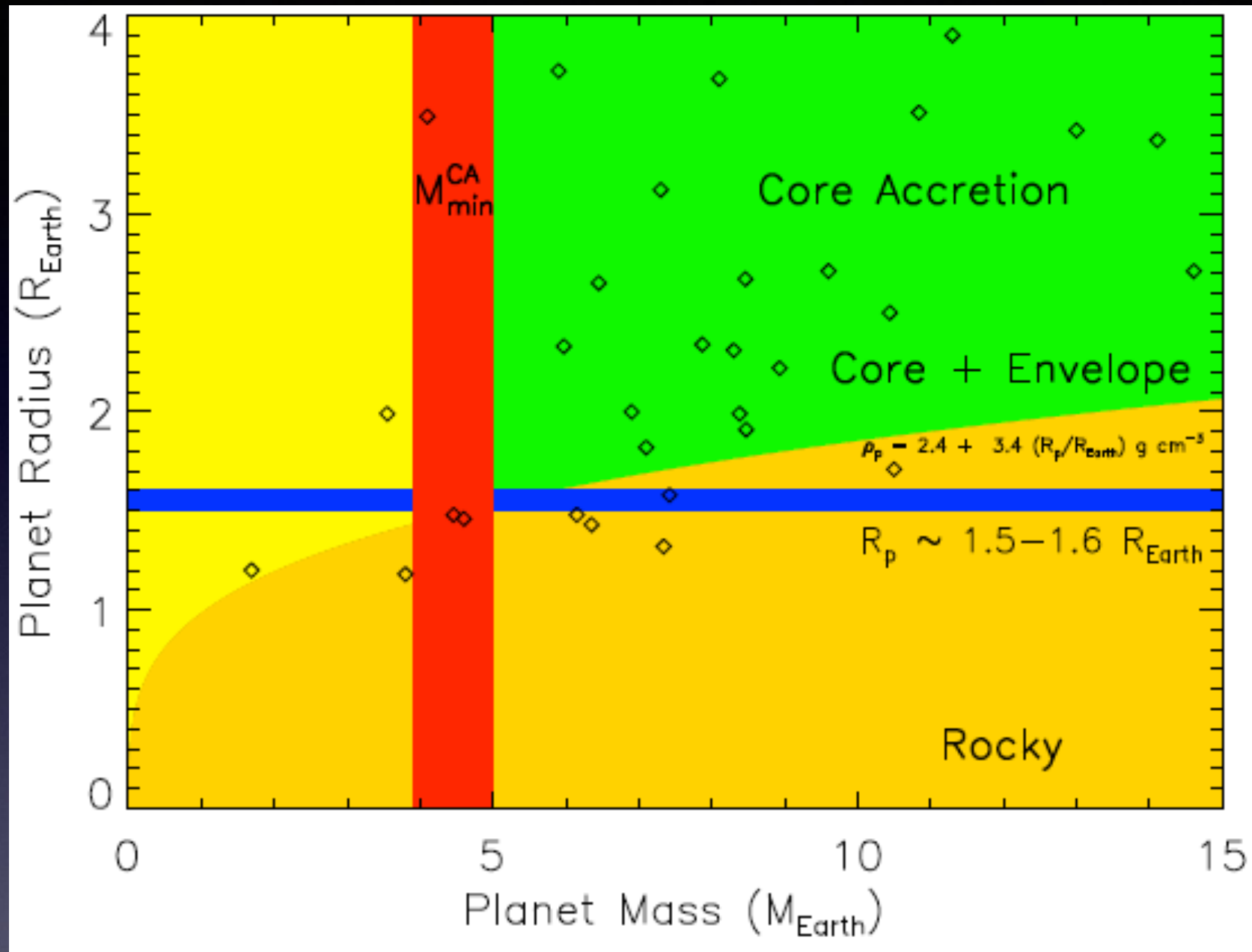
The Minimum Mass of Planets Formed by Core Accretion at Planet Traps:

$$M_{min}^{CA} \simeq 4 - 5 M_{\oplus}$$



# Switching of Migration Modes at $M_{min}^{CA} \simeq 4 - 5 M_{\oplus}$

Hasegawa 2016



## Planet Traps

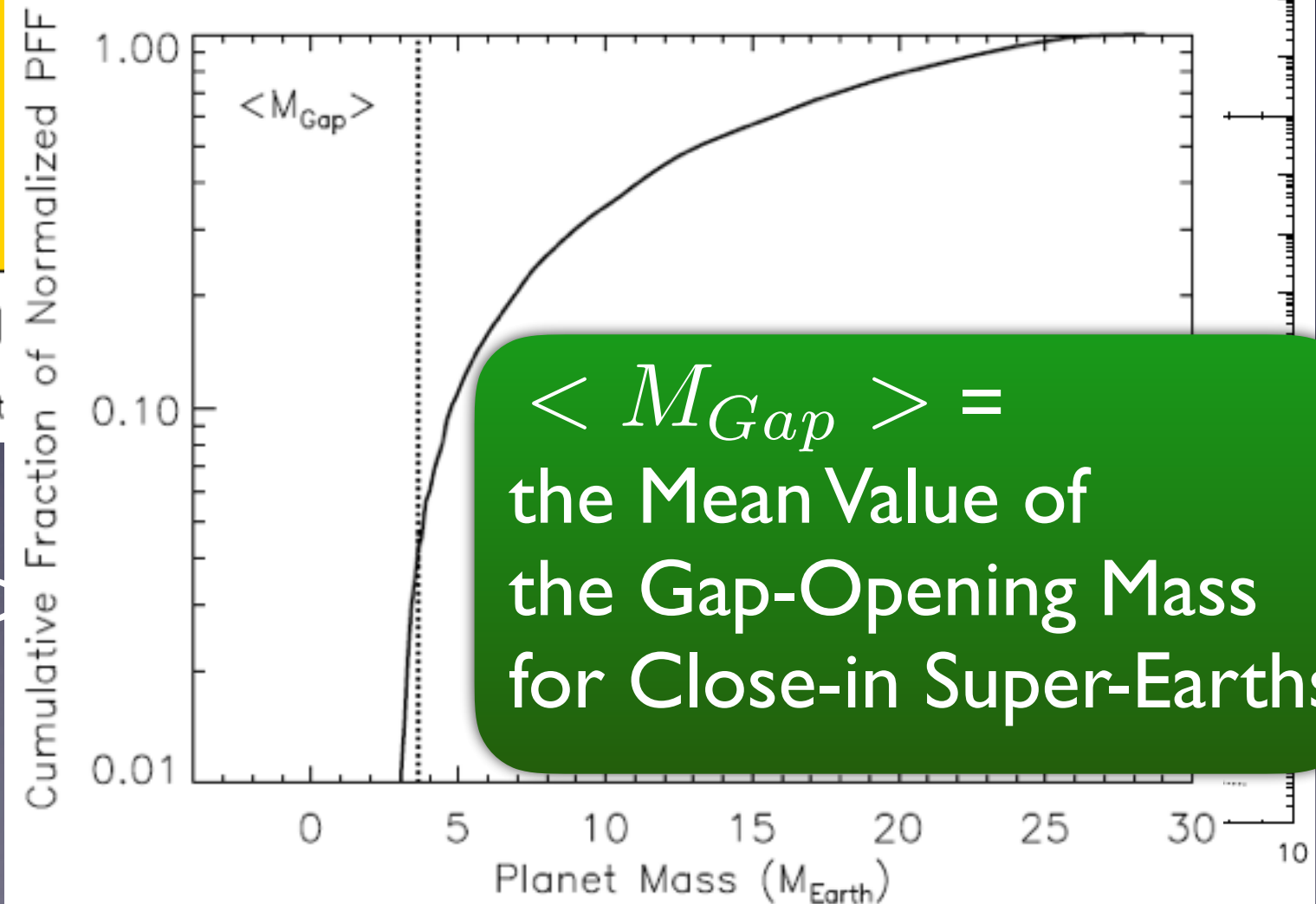
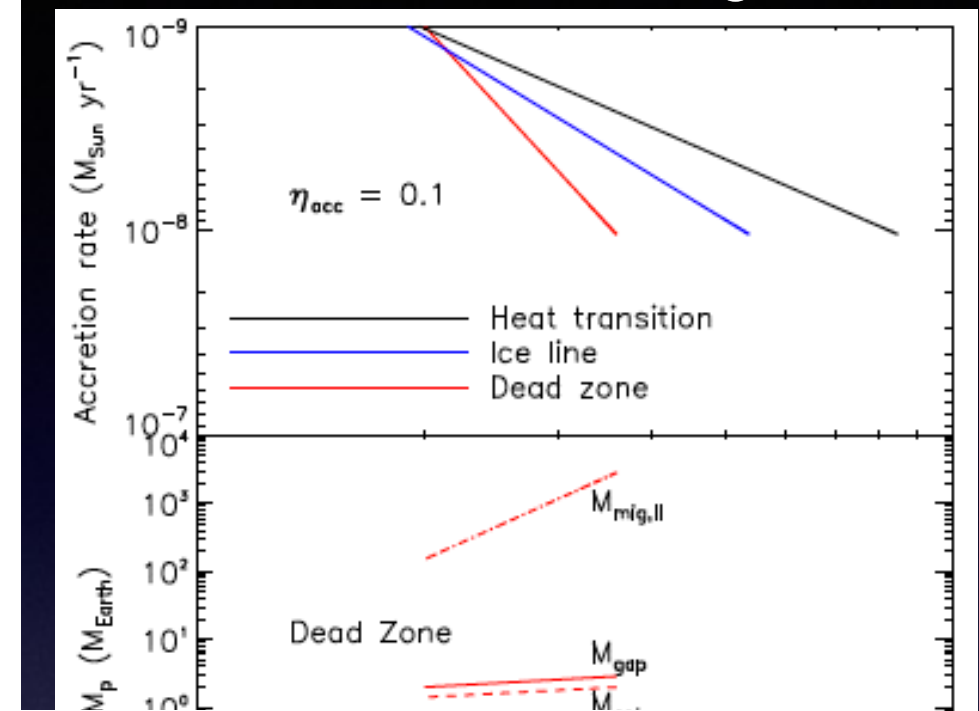
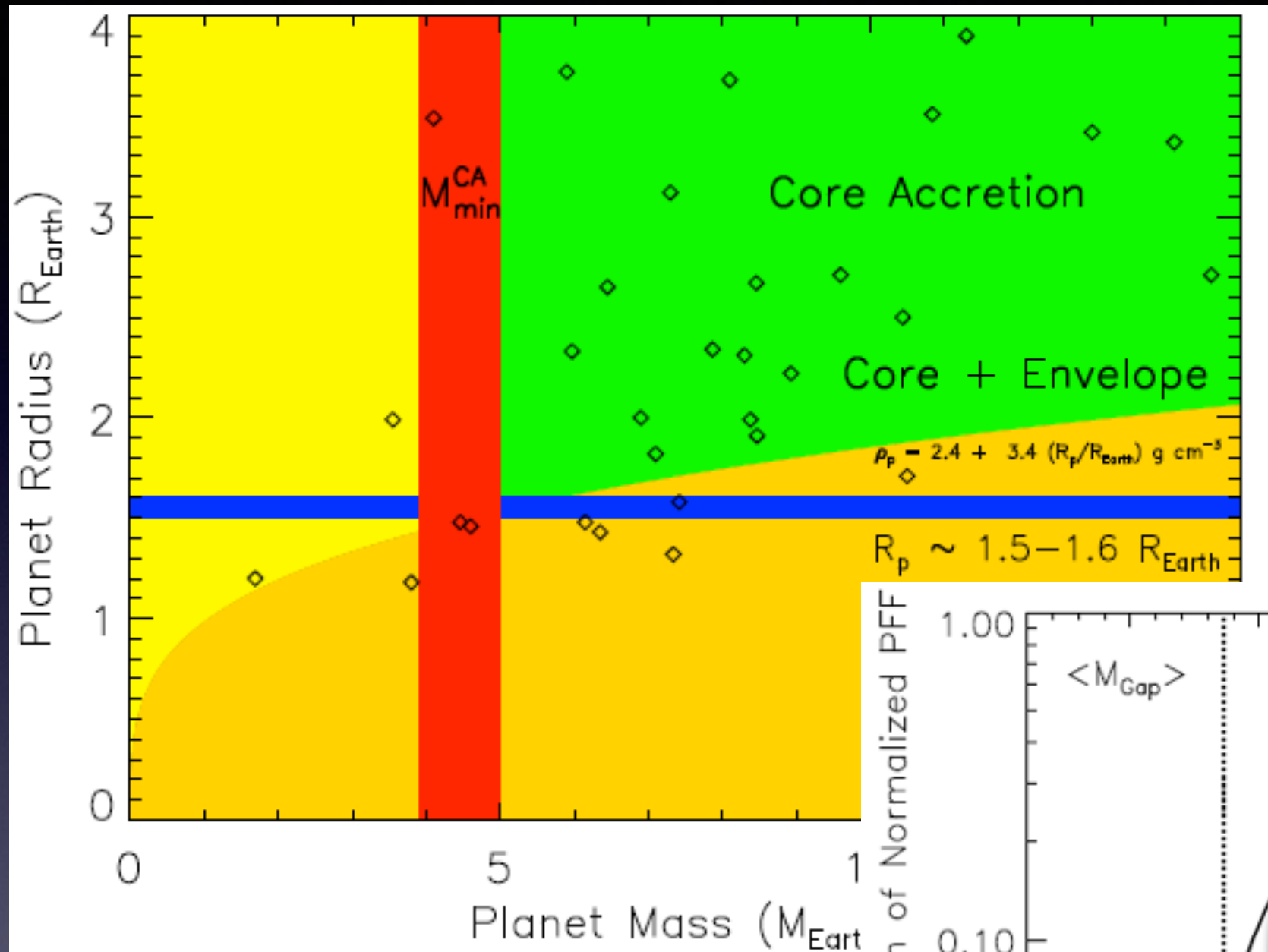
:Transport Forming Planetary Cores  
from Large Orbital Radii to  $> 1 \text{ AU}$

## Type II Migration

:Transport the Cores from  $r > 1 \text{ AU}$  to  $r < 1 \text{ AU}$

# Switching of Migration Modes at $M_{min}^{CA} \simeq 4 - 5 M_{\oplus}$

Hasegawa 2016



$\langle M_{Gap} \rangle =$   
the Mean Value of  
the Gap-Opening Mass  
for Close-in Super-Earths

## Planet Traps

: Transport Forming Planetary Cores  
from Large Orbital Radii to  $> 1$  AU

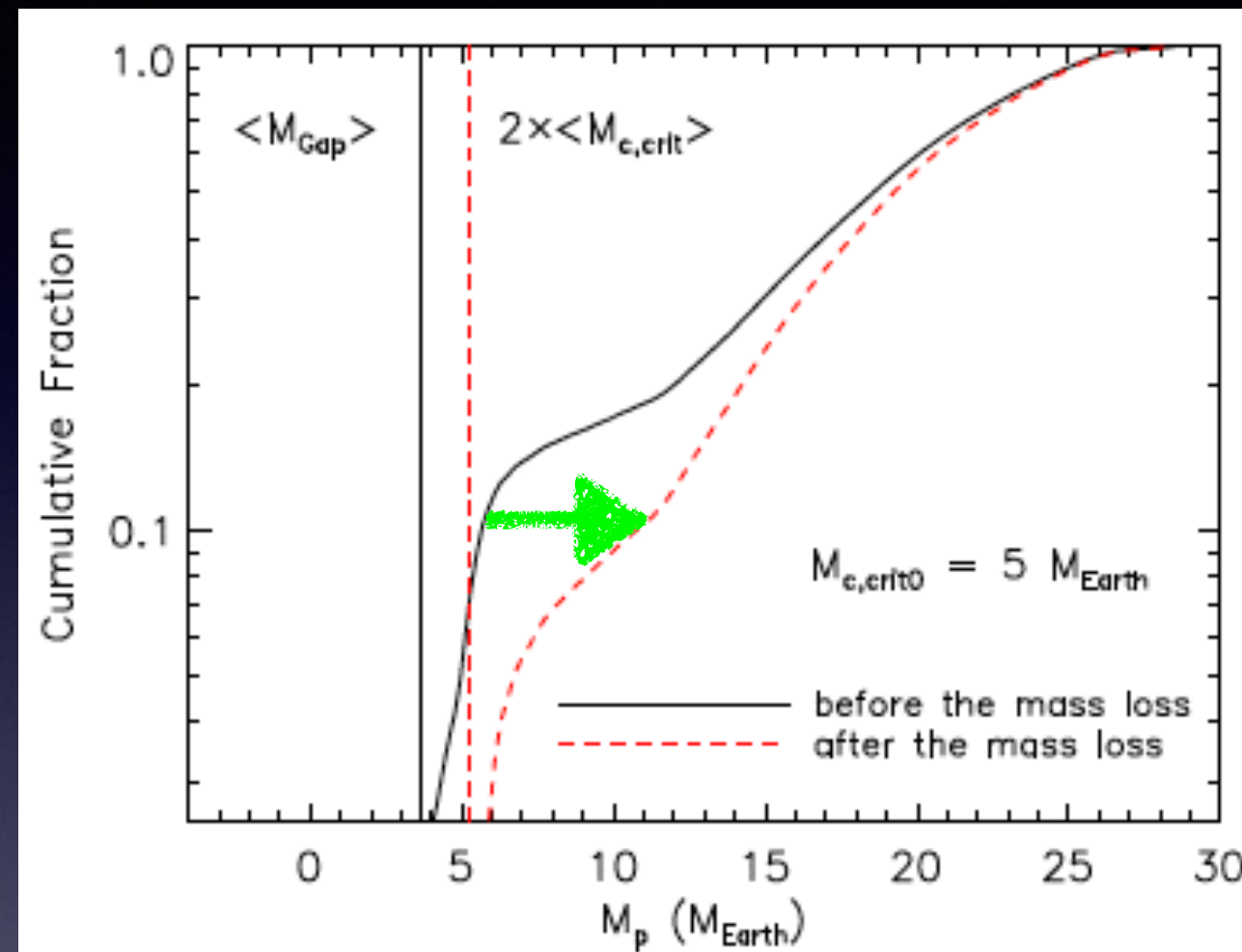
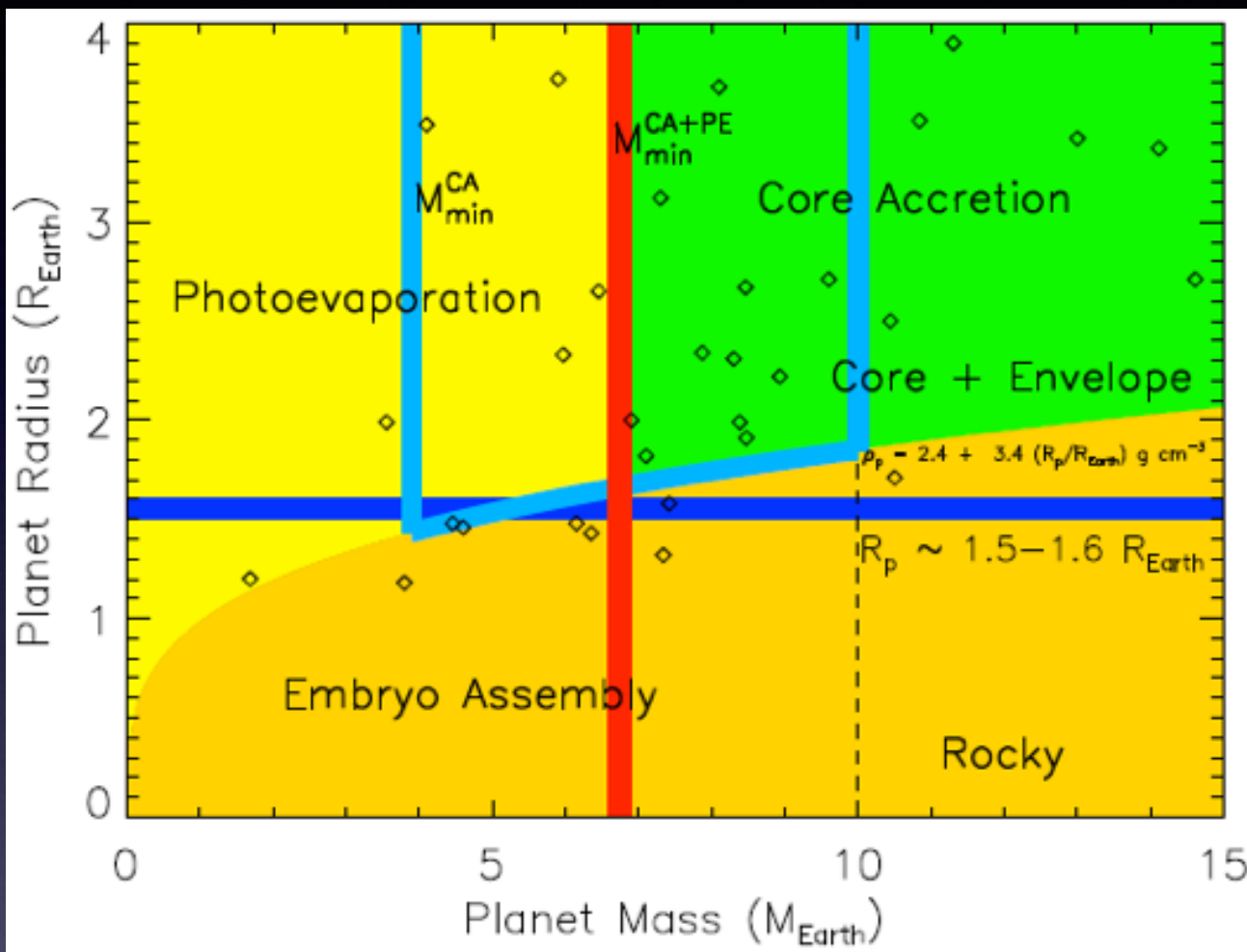
## Type II Migration

: Transport the Cores from  $r > 1$  AU



# The Effect of Atmospheric Escapes

Hasegawa 2016



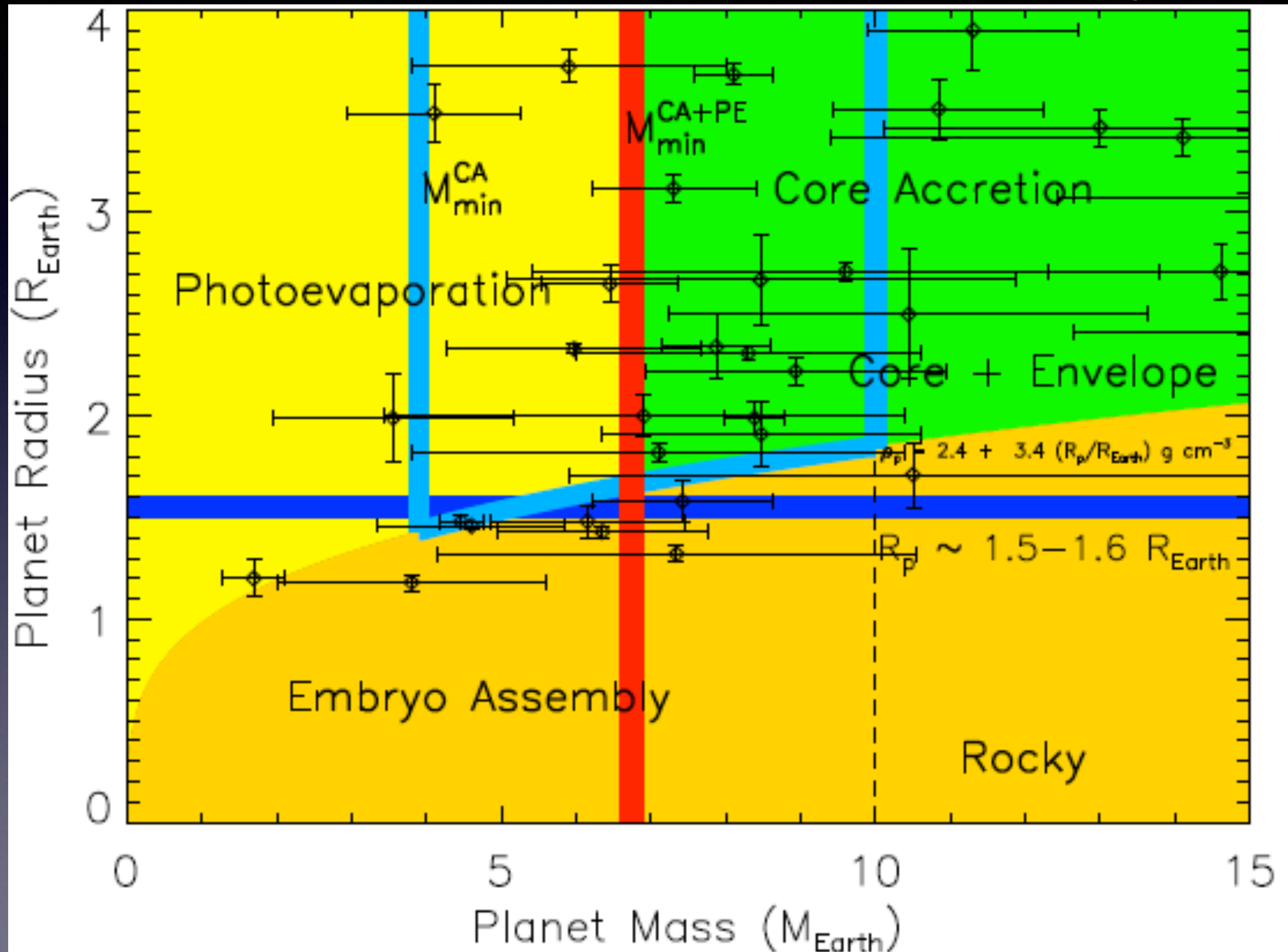
The Mass-Radius Diagram Divides into a Number of Regions, and can Specify the Histories of Close-in Super-Earths

The Photoevaporative Mass Loss Increases  $M_{min}^{CA}$  of  $\sim 5M_{\oplus}$  to  $M_{min}^{CA+PE}$  of  $\sim 7M_{\oplus}$  by Stripping the Gas Envelopes

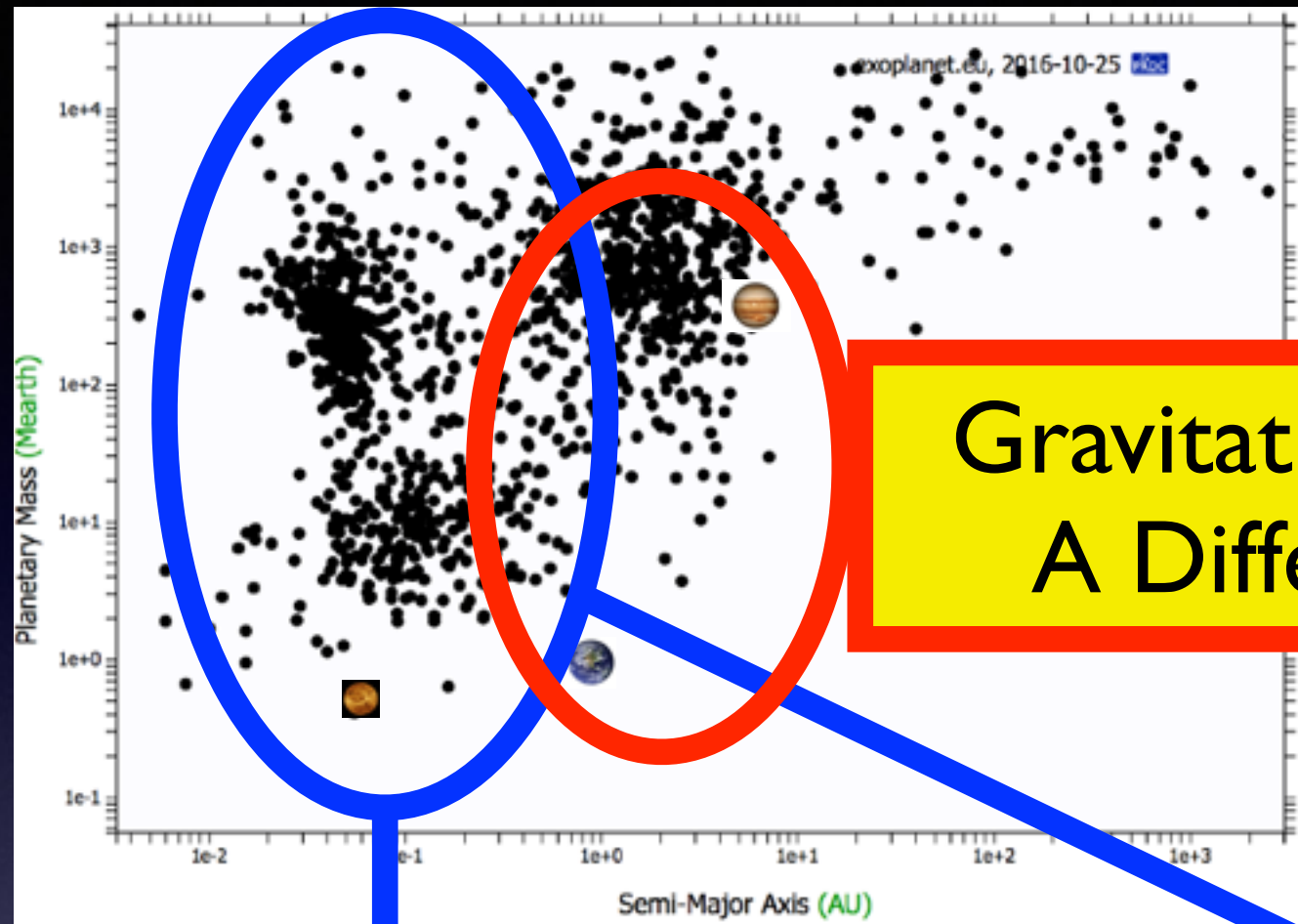
Lopez & Fortney 2013

# Exoplanet “Phase” Diagram

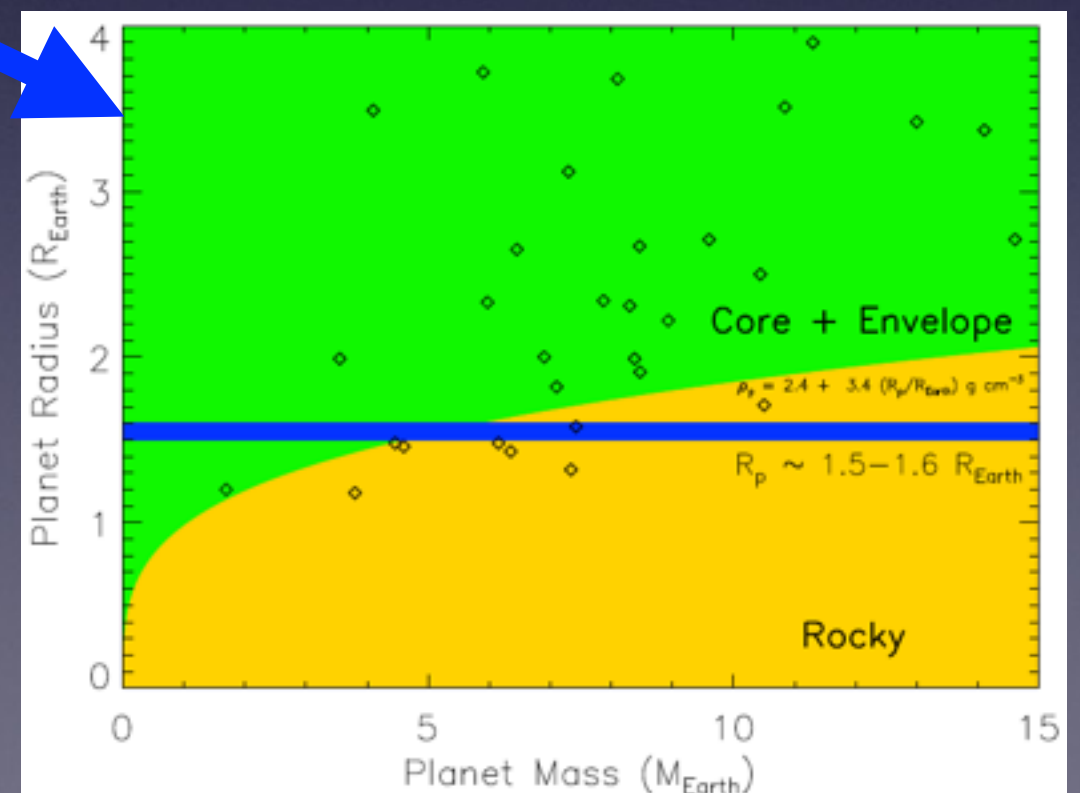
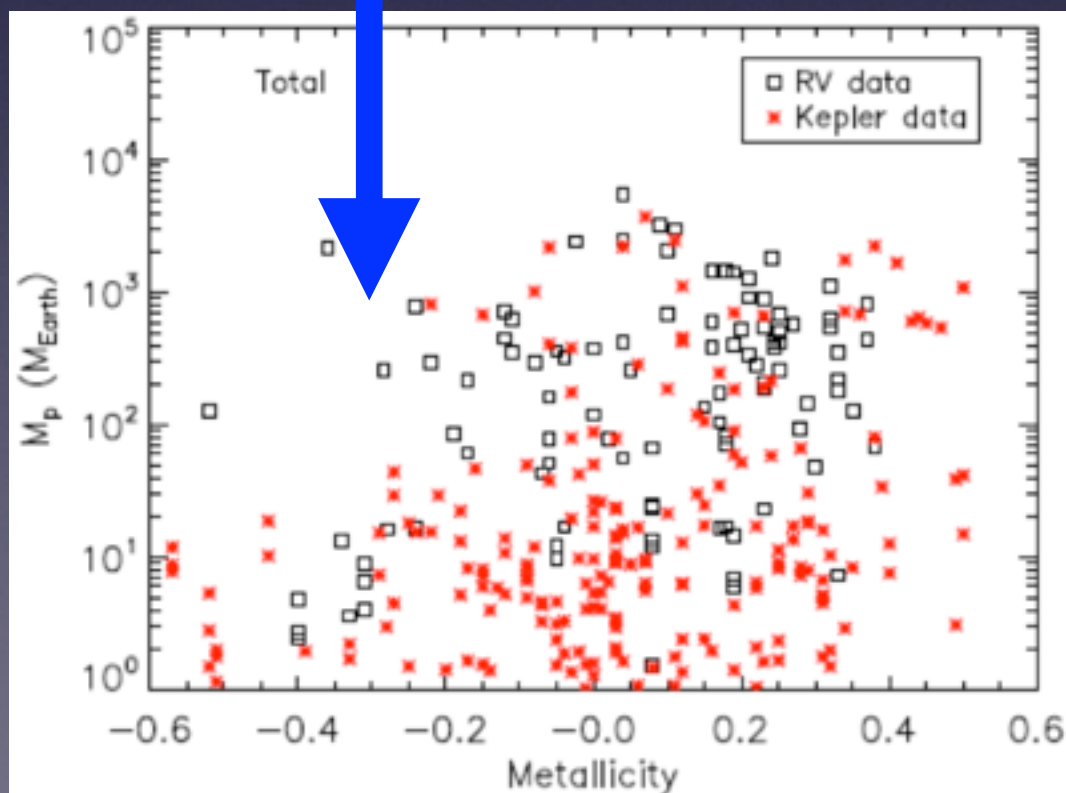
Hasegawa 2016



# Implications for Gravitational Microlensing



Gravitational Microlensing Covers  
A Different Parameter Space!!





# Summary

Hasegawa 2016, ApJ, 832, 83

- The currently observed exoplanetary populations are quite useful for deriving some constraints on theory of planet formation
- A population synthesis model is developed, focusing on Type I migration traps (dead zone, ice line, heat transition)
- Planet traps may be important to reproduce the trend of observed massive exoplanets, and for some fractions of observed close-in super-Earths
- Switching of migration modes determines the minimum mass of super-Earths formed by our model, which is  $M_p > 4-5 M_{\text{Earth}}$ , & the mass-radius diagram can serve as an exoplanet “phase” diagram
- (Future) gravitational microlensing observations can fill out a different parameter space, and would be useful for drawing a better picture of planet formation